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SPACE REVIEW STUDY: HUMAN FACTORS ENGINEERING'S ROLE IN UNMANNED SPACE OPERATIONS

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This technical report has been reviewed and is approved for publication.

FOR THE COMMANDER

MARIS M. VIKMANIS
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13. ABSTRACT ***(Maximum 200 words)***

This Space Review Study was conducted to ascertain the state-of-the-art in ground-based satellite control, estimate the impact of human error on satellite operations, review existing research in satellite control, and recommend a human engineering research and development program to reduce error and correct deficiencies. The Study found that much of contemporary satellite control uses legacy computer systems and display information in text format, while controlling using the command line interface. Later systems use windows and graphical user interface technology, which is only a small increment in functionality. The existing literature on satellite control is sparse because of the classified nature of many systems--reluctance to permit studies and/or data collection, or because of a reluctance to advertise error. The proposed human engineering research and development program advocates cognitive engineering of displays and control, modeling for design, testing and training, real-time satellite operations, intelligent agents and/or aiding, monitoring on-board automation, creation of an operator error data base, and extending display and control guidelines. Further, three different ways are described to facilitate the laboratory space program: collaborative partners, a common satellite model, and a shared research facility. There appears to be sufficient justification for a human engineering program addressing ground control of space operations. This research and development program will result in significant improvement in operational effectiveness, reduced manpower requirements, and savings in training costs.

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1. SPACE STUDY GOALS

Air Force Research Laboratory (AFRL) has initiated an unprecedented change in research direction toward realizing the space elements of the Air Force aerospace mission (Covault, 1999). Although space related research has long been a part of the overall research program, it has been a relatively small part. This redirection is a dramatic change from the aircraft related research, which has dominated the lab's budget, publications, and the accumulated expertise since the lab's inception.

The Human Effectiveness Directorate (HE) shares both aircraft heritage and a significant history of space related research. Historic aeromedical predecessors of the directorate were involved with the Mercury and Gemini NASA programs, inventing some of the equipment and methods flown (Dempsey, 1985). More recently, a telescope for direct earth observation research (Merkel, Task, Whitely, LaPuma, Pinkus, and Block; 1990) was developed and flown on the Space Shuttle.

Although the new Air Force space initiative does not preclude manned spaceflight, it is clear that for the foreseeable future most Air Force space operations will be of an unmanned variety. This has led to questioning what role the HE will have on AFRL's new space focus when unmanned spacecraft will be predominate. The purpose of this study is to examine carefully the 40 year history of unmanned spaceflight to determine whether there is a role for human factors and ergonomic engineering in such space operations and what exactly that role might be. This will be accomplished in a systematic four-step process.

1.1. Ascertaining the State-of-the-Art in Satellite Control

Satellites are controlled by some combination of on-board automation and human ground controllers. The first task is to describe how this is accomplished in contemporary Air Force, other Government, and commercial settings. This examination will seek to determine how satellite displays and controls are designed and implemented and identify specific elements needing attention. Satellite controlling is a part of the larger human-computer interface (HCI) problem, but space has unique aspects, which make it different from other HCI problems.

1.2. Estimating the Impact of Human Error on Satellite Operations

Over the 40 years of unmanned spaceflight, there have been many cases of vehicle loss. Some of those losses, including recent ones, can be directly attributable to human error. Although human error can never be completely eliminated, it can be minimized by attention to the human role in space vehicle operations. Human factors engineering has made significant contributions to reducing aircraft losses and there is every reason to believe similar safety improvements can be made in satellite operations.

1.3. Review Existing Research in Satellite Control

Any research program planning requires a thorough understanding of existing publications to serve as a basis for the plan and to avoid unplanned replications. Even if the existing literature is limited in scope, that certainly is critical information toward justifying initiating new research. This step will include a forward look toward anticipated demands on satellite operators.

1.4. Proposed Human Engineering Research and Development Program

Once the preceding goals are accomplished, the last step is to recommend a specific research program which will make important contributions to Air Force Space operations, compliment AFRL initiatives, assist other Government and commercial space ventures, and make a significant contribution to the scientific and engineering literature.

2. ASCERTAINING THE STATE-OF-THE-ART IN SATELLITE CONTROL

2.1. Current Satellite Operations Centers

2.1.1. Government

National Aeronautic and Space Administration (NASA) is arguably the premiere agency for space operations in the world. It directly controls or allocates control to subsidiary organizations of all civilian Government space vehicles.

Much, but not all, of NASA's ground controller software is hosted within windows and graphical user interface (GUI). Some functions are still performed by text-based software, as discussed later in the Mars Climate Orbiter Failure Report. The Space Shuttle launch control facilities recently transitioned into a new facility after operating for a decade in the 60's Saturn/Apollo control room. NASA maintains a consolidated planetary exploration control center, control centers at JPL, Johns Hopkins University, and other locations.

Human factors for ground controls displays are done at Goddard Space Flight Center (GSFC), Maryland. There, supported by the Pacific Northwest National Laboratory, the Information Systems Center (ISC) is pursuing improvements in ground controllers displays and controls. Fox, Breed, Moe, Pfister, Truszkowski, Uehling, Donkers, and Murphy (1999) describe display and control design using the user-centered design methods. Their approach includes cognitive modeling, rapid display prototyping, software prototyping, and usability testing. Fox cites a number of example applications where user-centered design has been applied including the Hubble telescope and Earth Observing System. GSFC/ISC is also conducting research in intelligent agents as aids to ground controllers (Truszkowski, Murphy, and Norman, 1999). Truszkowski *et. al.* examines anomaly processing which exceeds the capability of on-board automation. At issue is how fast can operators be updated on system status and aid in the solution of the anomaly. An earlier paper by Hartley and Hughes (1996) summarized earlier efforts to automate both on-board and ground-based operations. Clearly, any AFRL space research program would benefit from cooperation or collaboration with GSFC.

2.1.2. Military

Military satellite operations are conducted under the auspices of United States Space Command (USSC) and its separate Army, Navy, and Air Force Space components. Key players in AFSPC (AFSPC, Peterson AFB, CO) are its operational units, which actually operate the space assets. AFSPC's 50th Space Wing is the largest Air Force satellite operator, controlling over 50 satellites through its ten Space Operations Centers (SOCs) and employing 1300 space system operators.

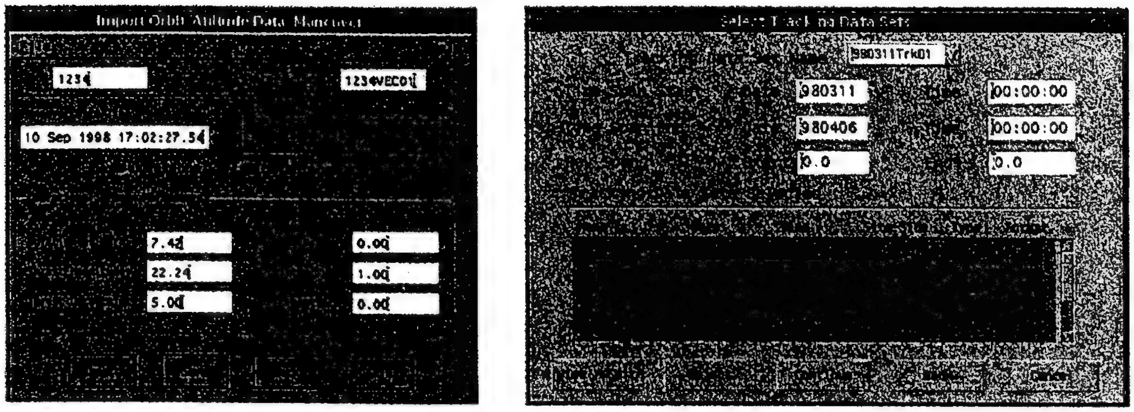
The state-of-the-art in military satellite control is heavily dependent on 1970's technology first introduced back with the first military space systems. Support computers are old and difficult to maintain mainframe technology running special purpose hardware and software. These legacy systems are expensive to maintain and even more expensive to modify, since nearly all contracting must be done sole-source to the original developers.

Each satellite control system is different. The systems were developed independently over three decades. The satellites are radically different in the missions, payloads, and subsystems. The user displays for these systems can be characterized as all text-based, displaying in some cases scrolling raw download data from the satellites. This interface puts a significant burden on the satellite system operators, requiring them to interpret and analyze disparate information without much machine assistance. Commands are issued via a command line interface (CLI) with checking manually performed by a second operator to ensure command accuracy.

The 50th Space Wing's Operations Group manages operator training. Training satellite operators is primarily done using paper course materials and console mock-ups. The Operations Group has a Satellite Operations Simulator Section, which develops and manages satellite operations simulators. However, there is a heavy reliance of on-the-job-training (OJT).

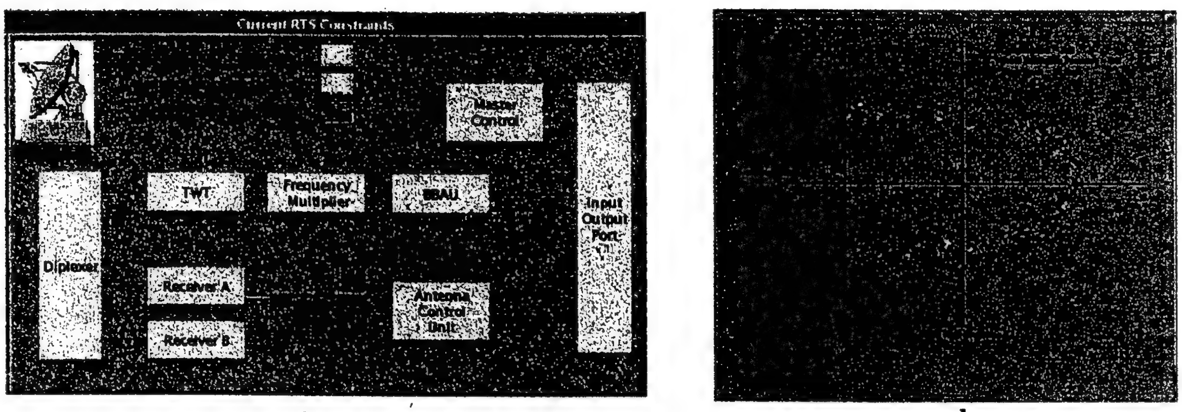
Technology development and insertion into space operations is done through several organizations. AFSPC operates the Space Warfare Center (SWC), Schriever AFB, CO, which is tasked with advancing space tactics development, testing, analysis, and training programs. SWC operates the Space Battle Lab (Schriever AFB, CO) which identifies innovative space operations and logistics concepts and measures their effectiveness. Air Force Materiel Command (AFMC) supports acquisition and logistics for space through its Space and Missile Systems Center (SMC) (Los Angles AFB, CA). SMC operates the Center for Research Support (CERES, Schriever AFB, CO) to discover and test commercial off-the-shelf (COTS) technologies to support AFSPC. CERES is particularly active, having established laboratory test facilities and conducting evaluation of several COTS systems for possible use by AFSPC.

SMC participated in a Human-Machine Interface Working Group (HMIWG) with support contractor Lockheed Martin and Aerospace Corporation. A compact disk of example formats was obtained and can be characterized as translation of the text-based displays into contemporary windows and GUI format. The first two formats are examples of the HMIWG proposed displays employing text representations with buttons and pull-down menus (Figures 2.1.2-1a and b). The second two formats (Figure 2.1.2-2a and b) introduce graphical representations. Figure 2.1.2-2a shows a block diagram of systems and their status. Figure 2.1.2-2b shows the positional drift of a satellite relative to its assigned location, although employing the satellite image in this case seems of little value. These HMIWG formats represent a significant step forward in display design. However, display formats employing such research concepts like cognitive engineering and intelligent aiding can perform even better than these displays based on the contemporary desktop paradigm.



a. b.

Figure 2.1.2-1. HMIWG formats which place text information in the Windows and GUI format paradigm. Notice the use of buttons and pull-down menus.



a. b.

Figure 2.1.2-2. Graphical representations of information including block diagram (a) and an X-Y plot (b).

The problems associated with satellite ground station displays and controls are understood, but the operational community has been slow to respond. Modifying legacy systems is expensive and disruptive of operations. The operations community solution is to increase staffing of controller crews to compensate for their displays and control problems with more crewmembers. This near-term, problem-solving strategy is both shortsighted and expensive. The long life cycle of space systems means that manpower costs will be prohibitive. Additionally, the labor-intensive solution may actually increase the chances of operators making a significant error in satellite operations.

2.1.3. Commercial

There are COTS hardware and software systems for satellite control. Lockheed Martin offers its Space Control System-21™ (SCS-21™). SCS-21™ is based on commonly-used hardware platforms (workstations), uses Ethernet communications, a GUI interface, and talks to a variety of common third party hardware. At least 15 commercial geosynchronous

communications satellites employ SCS-21™ in their day-to-day operations and the CERES Air Force facility at Schriever AFB, CO is evaluating it for military applications.

Additionally, a telephone interview was conducted with the manager of the IRIDIUM™ telephone satellite constellation. The IRIDIUM™ satellite constellation consists of 66 orbital vehicles located in low earth orbit (760 km, 485 miles) in six different orbital planes and in number of vehicles and is probably the most complex satellite system in existence. The IRIDIUM™ control center employs a proprietary software system based on GUI interface in control of the constellation. According to the control center manager, the control software was contracted out and was unsatisfactory as delivered. They have evolved a spiral development method with software engineers working in the control center to evolve their displays and controls to where they consider the system effective. Their biggest problem is maintaining status on all the spacecraft, which differ in block configuration and in their current operational state.

It appears that commercial satellite control systems are approaching and surpassing the complexity of military systems. Close Government ties to these commercial operators while protecting the proprietary nature of their systems (the satellite telephone business is competitive) can result in beneficial exchanges between the two communities.

2.2. Existing Standards and Guidelines

The only existing standards and guidelines that were found for space-related displays and controls were published by NASA (NASA-STD-3000) and several publications of American Institute of Aeronautics and Astronautics (AIAA). NASA-STD-3000 is similar to MIL-SPEC-1472D as it favors a more anthropometric and physical ergonomic view. Volume 1, Section 9 covers workstation design and illumination, switch configuration, labeling, etc., and virtually nothing about display format, symbology, or anything cognitive about HCI in general or satellite control in particular. Goddard Space Flight Center has published an outstanding set of guidelines for controls and displays, "User-Interface Guidelines," DSTL-95-033. This document contains guidance for basic interface components, screen layout and design, interaction styles, window management, visual coding techniques, and user feedback.

Several of the AIAA publications also deal with ergonomic design, but are quite specific to satellite-related issues. These publications include AIAA G-042-1991--AIAA Guide to Design for On-Orbit Spacecraft Servicing, and AIAA G-056-1992--Guide for Berthing/Docking/Grasping interfaces for Serviceable Spacecraft. Proposed Guide G-042-1991 is typical of these publications and deals with design for on-orbit spacecraft servicing. An outgrowth of NASA workshops, assembled by NASA with the help of industry to recommend specific configurations to facilitate on-orbit service activities by astronauts and cosmonauts. The guide provides several case study examples from the space station, advanced x-ray astrophysics facility, and other orbital systems to illustrate its design strategies, including sample checklists for the service operations. Given the study focus on unmanned satellite control, this publication and related ones on manned spaceflight are only of peripheral interest.

Perhaps the most interesting of the AIAA publications is American National Standards Institute (ANSI)/AIAA R-023A-1995--Human-Computer Interfaces for Space System Operations. Based on the list of collaborators, this standard grew out of the military satellite

control community and its support contractors and seems to be an effort to consolidate the approach of Air Force contractors for what became the SOC. The standard does a fine job of addressing a common look, feel, and operation for satellite control consoles. The standard goes as far as to recommend a standard layout based on a conventional windows GUI. The windows are tiled with cascade instead of layered so as not to hide critical information, providing sliders to scroll within a window (Figure 2.2-1).

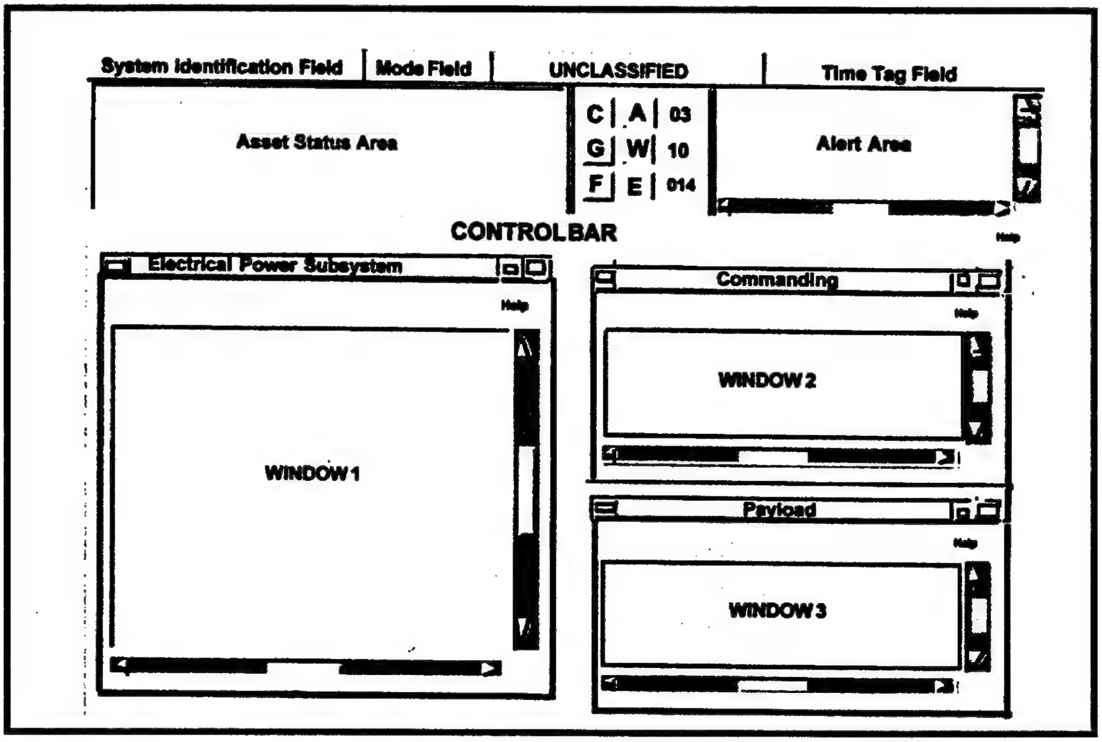


Figure 2.2-1. Recommended Window Layout From ANSI/AIAA R-023A-1995

Also provided are a set of icons for a variety of satellite boosters, control tasks, systems, subsystems, ground systems, and other items. Examples of some of these icons are seen in an example display (Figure 2.2-2).

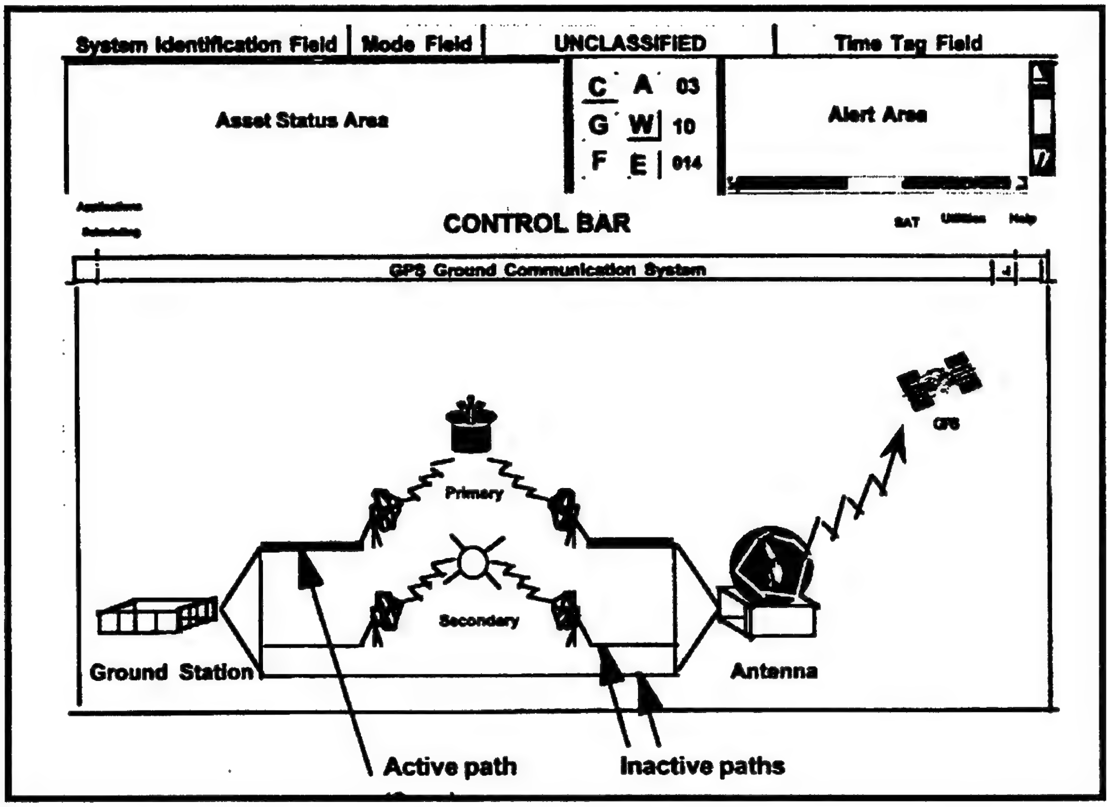


Figure 2.2-2. Example Display With Icons From ANSI/AIAA R-023A-1995

The ANSI/AIAA standard defines a very comprehensive list of core interface requirements (display control, messaging, alerting, error correction) and some extremely insightful enhancements (on-line help, messaging, graphics, decision support, computer-based reasoning). The requirements for these interface operations are given along with useful guidance examples, however, details about implementation are not provided. Without more specific guidance, displays can satisfy the requirements with vastly different formats and controls, leading to the current situation of unique displays for each satellite.

The lack of detail recommendations can be attributed to several causes. Foremost is probably the desire to not restrict the contractors who must deliver the working systems (at least seven different contractors are listed as participating) and mirrors the growing trend away from unnecessary specifications. Another possible cause is that each satellite system is unique, so one "specification" may not fit all satellite systems. This topic came up several times during interviews and raises the interesting issue of abstraction in satellite control. It seems as though except for differences in the payload, a large number of satellite operations are common among platforms and differ only in how they must accomplish those common tasks. For example, alignment of a satellite ought to be the same for all satellites, with the means of the realignment (reaction wheel, thruster, etc.) transparent to the operator. System or subsystem peculiarities ought to be only made visible if remedial action requiring details of their implementation is necessary to understand the fault situation. The consolidation of displays for directing common satellite operations and for monitoring common satellite systems and subsystems while managing

unique details of each satellite mission and hardware would reduce workload, training, and allow controllers to more easily transition between different systems. Augmenting the ANSI/AIAA guidelines could be considered a major deliverable of a design and research program.

3. IMPACT OF HUMAN ERROR ON SATELLITE OPERATIONS

One of the most pressing reasons to do research to improve satellite control and operations is the huge cost of error or failure associated with satellite operations. The recent boost-phase failure of a Titan IIIC with a military communications satellite was valued at $1.2 billion (Atkinson, 1999; Mann, 1999). The failure was eventually attributed to an inaccurate software load by contractors. Military satellite losses inevitably reduce operational effectiveness, erode public relations with Congress, and can reduce public support for military space operations; the value of these losses is difficult to measure. Therefore, modest investments to reduce or prevent human error from causing or contributing to satellite losses will pay huge dividends to the Air Force.

3.1. Press Reports

Much of the early failures in satellite operations are shrouded in secrecy or not very well documented. The press has revealed several instances where human error played a role in satellite loss. Although some of these errors had insignificant effects on the mission, even innocuous errors can trigger sequences of events, which lead to serious consequences. Any departure from nominal operations must be considered serious because of the potential for cascading errors. Such was the case of the NASA-ESA Solar Heliospheric Observatory that was investigated in-depth and is discussed later.

The Russians have identified human error in space missions on a number of occasions. In 1988, a Soviet Soyuz manned capsule commander confessed to nearly causing a fatal accident when he restarted a breaking rocket during a failed landing maneuver (L.A. Times, 1988). The Phobos 1 Mars probe lost contact because a spacecraft controller failed to pass the last byte of a software load to Phobos I space probe as the reason it lost orientation and communications (Dye, 1988). A Russian cosmonaut's error handling docking of a Progress supply rocket with the Soviet/Russian Mir space station provided the highest drama, since the Mir was damaged and the crew's lives put at risk (Filipov and Chanler, 1997). Later, the same Mir crew (different cosmonaut) inadvertently disconnected a computer causing loss of attitude control.

The Russians are not alone in encountering human error in space operations. The highly regarded Mars Pathfinder mission lost a full day of exploration when a controller miscalculated a communication time by 11 minutes, resulting in transmission of computer commands to the lander when its receiver was turned off (Wilford, 1997). It took several hours to determine the cause of Pathfinder's inaction--too late to retransmit the commands in the same day.

Even Space Shuttle operations have been affected by human error (Associated Press, 1990). A ground generated signal caused the Shuttle Columbia to start a slow three degrees per second spin while the crew slept. A glitch of undisclosed origin commanded the spin and the crew had to be awaken to manually eliminate the spin.

An erroneous computer command sent by ground controllers caused an interruption in the Magellan spacecraft's mapping of Venus (Washington Post, 1990). It is uncertain

whether the command was sent in error or whether it got corrupted in transmission and reception. The spacecraft's signal was lost for 40 minutes during the incident.

NASA also acknowledged that technicians misaligned on the rocket the Far Ultraviolet Spectroscopic Explorer (FUSE) satellite by 5.3 degrees prior to its successful launch 24 June 1999 (Aviation Week, 5 July 1999). The error was discovered several days before launch and was deemed not a threat. Boeing technicians made the error and NASA reviewed and approved the installation. It was not detected until the spacecraft's own laser ring gyroscope reported the error. Often these kinds of errors are attributed to process mistakes or the failure to follow approved procedures.

3.2. Case Studies of Human Error During Spacecraft Operations

More important than the press reports of satellite losses are the after-accident investigations. Several reports have been published about operator errors resulting in aircraft loss. These reports are valuable not only for the attribution of blame, but also for the proposed remedial actions.

3.2.1. Human Error in the Space Systems Engineering Data Base

The Aerospace Corporation maintains the Space Systems Engineering Data Base (SSED) which tracks anomalies in spacecraft launch and operations including NASA, DoD, foreign Government, and commercial ventures. At the request of the AFRL, a search of the SSED was conducted to identify all human error induced anomalies since the 1950's (Arnheim, 1999). The data base contains a total of 9,678 anomaly reports, of which 441 are ground station operations with human factor implications (4.6%). It is important to note that mistakes and errors, which do not significantly affect the mission, are not reported in the SSED. Also, the SSED includes reports only on unclassified launches and payloads. This means the SSED reports are a conservative estimate of the size of the human error problem--they are the visible "tip" of what is likely to be a larger "iceberg" of problems caused by human error.

Eight catastrophic failures were attributed to human error. Six of these occurred between 1957 and 1962--very early in space operations. Four of these six were attributed to range safety officers intervening and destroying vehicles prematurely. The other two were misconfigured launch vehicles, which resulted in boost phase failures. Interestingly, the remaining two losses occurred in the past two years. These were the Solar Heliospheric Observatory (SOHO) satellite and Mars Climate Observer losses (detailed in following reports).

Four additional satellites suffered significant mission losses due to human miscues. One of these was a procedural error while the other four were erroneous commands transmitted to spacecraft. Procedural errors and incorrect command transmission are the two most common forms of human errors. Figure 3.2.1-1 shows how human error fits in the larger picture of ground station induced anomalies. All figures were directly copied from Arnheim (1999).

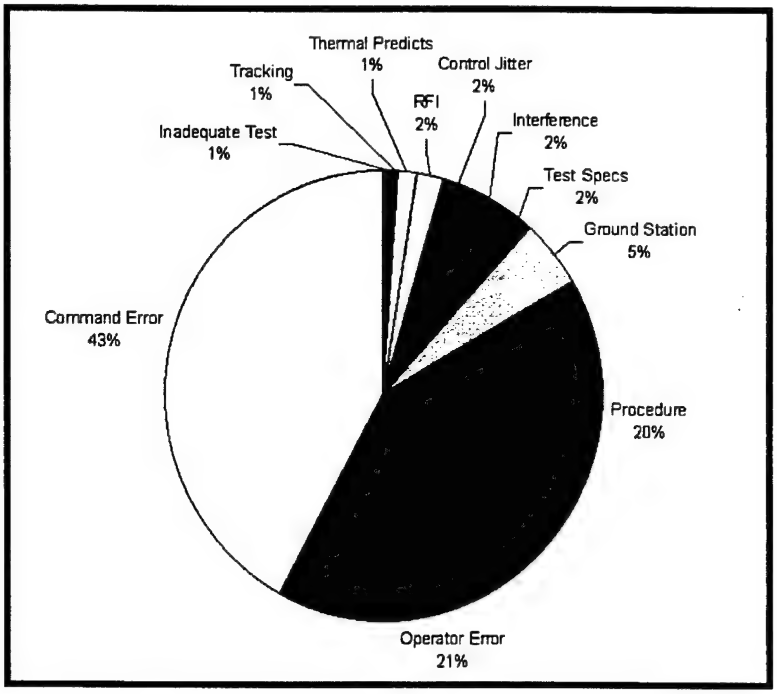


Figure 3.2.1-1. Distribution of Operational Anomalies Attributed to the Ground Station (SSED).

Many more low impact errors were recorded in the data base. These errors did not terminate or degrade the mission, but resulted in such consequences as payload data loss, high fuel expenditures, and the like. The breakdown of these lesser consequences of human error is shown in Figure 3.2.1-2.

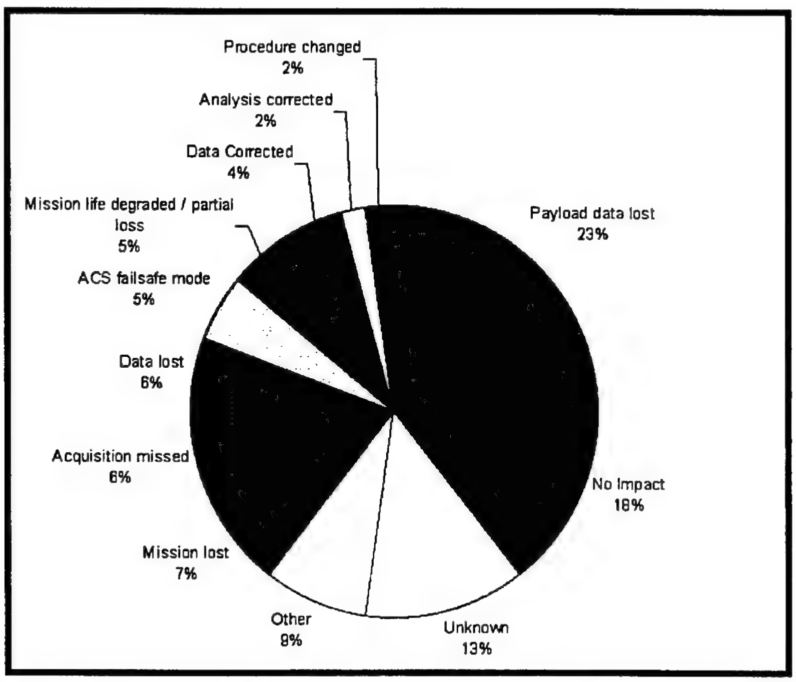


Figure 3.2.1-2. Impact of Operational Anomalies Due to Human Error (SSED).

The types of human errors in the SSED are shown in Figure 3.2.1-3. Although the breakdown is not very detailed, most of the errors are attributable to procedure execution and command errors (37% each). The remaining 26% of errors were lumped into the non-descriptor operator error or other categories.

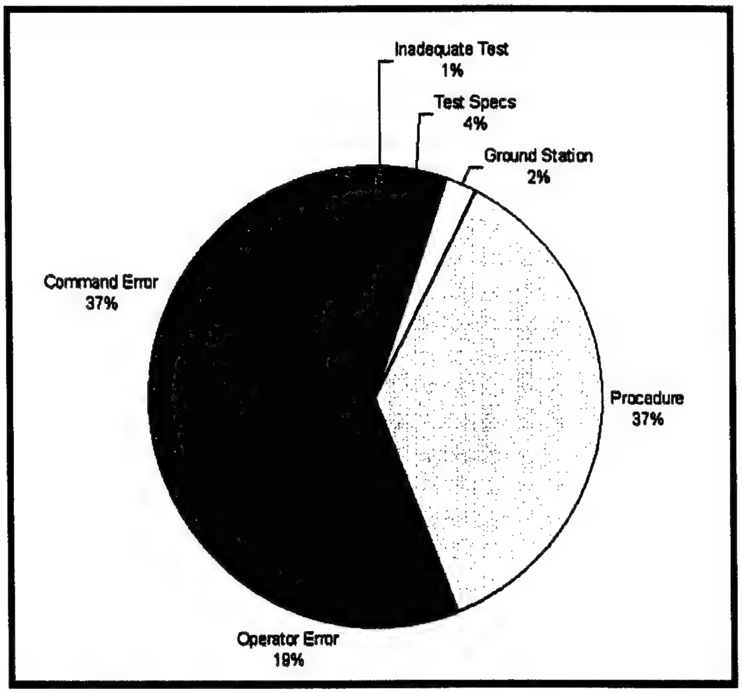


Figure 3.2.1-3. Types of Operational Anomalies Attributed to Human Error (SSED).

Searching the corrective recommendations of the SSED data, Arnheim and Tosney reveal that most recommendations are for more training/rehearsals, better procedural discipline, and better procedures (Figure 3.2.1-4). Lesser causes identified are situation awareness, loss of understanding configuration, and high pressure or information overload.

The individual incident summary included with the report reveals several interesting observations. First, the number of reports varies greatly from spacecraft to spacecraft. The Hubble Space Telescope has sixteen different human error reports. There are several explanations for the variance in numbers. First, some programs may be more diligent in reporting their human error-related problems. Second, some spacecraft are more command intensive than others and so are more prone to operator error. Hubble is continuously redirected to image targets and probably fits in this category. A second trend evident in the spacecraft with multiple incident reports is that there seems to be an increase in intervals between reports as the mission progresses. This indicates a "learning curve" in operations and that ground controllers appear to be learning how to handle the spacecraft through "OJT" training. This is a dangerous approach to controlling expensive space vehicles that can be irrecoverably lost.

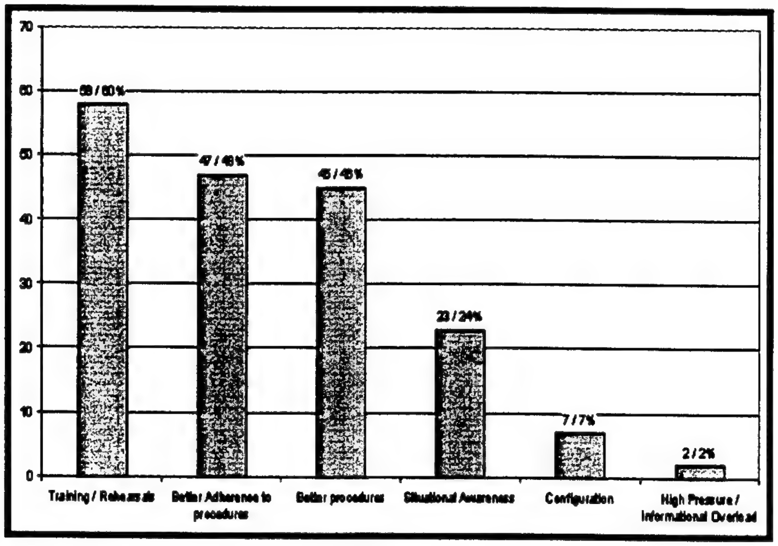


Figure 3.2.1-4. Potential Areas for Corrective Action in the Prevention of Operational Anomalies Caused by Human Error (SSED).

The low incidence of high pressure and information overload incidents really reflects the circumstances of most satellite control centers. Most spacecraft internal and orbital changes are preplanned and not real-time in nature. If a procedure is going slowly or if a problem develops, the standard operating procedure is to cease activity, reevaluate the situation, and complete the activity during a later orbit. It would be interesting to see whether this category is higher in classified intelligence gathering spacecraft where there are limited windows of opportunity to collect information on ground targets. Real-time control systems, like a space-based defense system, would also create more high pressure and information overload related incidents.

The report contains a detailed breakdown of each incident, its cause, and its consequences. In their summary, Arnheim *et al.* concludes "human errors can have a significant impact on mission life, a focus on the human factors and prevention of man-made operational anomalies can improve the chances of a successful and long lived mission." They recommend the most effective remedial actions are discipline and technical thoroughness. Further, training and flight-like rehearsals can enhance the expertise and experience of controllers and significantly reduce human error.

3.2.2. Solar Heliospheric Observatory Loss and Recovery

Perhaps the most striking documented case of operator error affecting satellite operations is that of Solar Heliospheric Observatory (SOHO), a joint NASA and European Space Agency (ESA) cooperative project. Contact with the functioning SOHO spacecraft was lost 25 June 1998 during a series of calibration, maneuvers, and reconfigurations. The remarkable recovery of SOHO by cleaver engineers also resulted in an exact determination instead of speculation for the loss of contact (Hellemans, 1998). The investigation board report (1999) determined the loss "was a direct result of operational errors--a failure to adequately monitor spacecraft status and an erroneous decision which disabled part of the on-board autonomous failure detection." (page 5)

As in any accident, multiple causes converged to produce SOHO's loss-of-control. The automated scripts used to perform routine changes were not properly tested and the key gyroscope (Gyro-A, which is one of three) was left despun when it should have been operating. The gyros were periodically shut down to increase their operational life. At the end of the script in question, a second (Gyro-B) was erroneously left in a high-gain setting which produced telemetry roll rates 20 times greater than were actually occurring. The "apparent" discrepancies between the gyros resulted in an Emergency Sun Reacquisition (ESR-5, the fifth time since launch that an ESR occurred), a safe mode allowing recovery of communications with the satellite. Controllers did not take sufficient time to analyze the cause of the ESR-5, ascertained the Gyro-B gain error, but missed the fact that Gyro-A was still despun.

Upon recovery from ESR-5, things continued to get worse. The attitude control system continued to use input from the despun Gyro-A and triggered thruster firings to counter its erroneous output. The resulting thruster induced roll caused the still operating Gyro-B to trigger an ESR-6. Controllers then interpreted the disagreement between the output of Gyros A and B to be caused by an error in Gyro-B and commanded it to shut down. The controllers commanded Initial Sun Acquisition (ISA) using the thrusters under control of the attitude control system, which was still responding to the erroneous output of Gyro-A and degraded the ESR safe mode controller. Again, thruster induced spin triggered ESR-7, another safe mode. However, this time, coupled torque of the thrusters and lack of gyro input combined to overcome the ESR controller and spacecraft attitude control was lost along with thermal management, solar cell orientation, and communications.

The board listed 13 direct and indirect contributing causes to the loss-of-control of SOHO. Of those causes, many can be considered human factors related. Those aspects of human factors implicated are workload, situation awareness, display design, communication breakdown, training, and decision processes. The following are the 13 causes with comment on those human factors related.

1. Failure to control change.

2. Failure to perform risk analysis of a modified procedure set.

3. Failure to communicate change.

   Part of any configuration control system is proper naming to identify modifications. The operational script which triggered the events leading to SOHO's loss was named A_CONFIG_N and in its original form, properly managed Gyro-A. This script was modified later in the program and these modifications introduced the error of leaving Gyro-A despun. Lack of configuration control and failure to rename the modified script resulted in a failure to properly test the modified script. Communication of the change by renaming the script would have resulted in proper testing of the new script.

4. Failure to properly respect autonomous Safe Mode triggers.

Under time pressure to satisfy an aggressive science schedule, controllers failed to fully analyze the conditions leading to the ESRs. An ESR is designed to last up to 48 hours, so there was sufficient time to fully research and make decisions. The telemetry frames transmitted with each ESR were not examined, in part because of display problems. Decisions were made in a hurry and based on insufficient information.

5. Failure to follow the operations script--failure to evaluate primary and ancillary data.

   The Flight Operations Team (FOT) exhibited poor situation awareness of Gyro-A despun state. However, the accident board review of telemetry also discovered that three of the four battery discharge regulators were disconnected from the spacecraft bus. This condition existed for at least several months prior to SOHO loss and was unknown to the controllers! Though the improper configuration did not figure into SOHO's loss-of-control, it meant that the duration of telemetry transmission would be only minutes after attitude control due to restricted access to the batteries.

6. Failure to question telemetry discrepancies.

   The discrepancy between Gyro-A and B should have raised major concerns among the FOT. Roll rate confirmation could have been deduced from sun sensor data. One cannot help wondering how the FOT displays affected correlation of data from different telemetry sources. Additionally, the shutdown of Gyro-B apparently violated standing procedures. A Materials Review Board (MRB) should be convened to review disabling a key component like a gyro. The ESR's 48-hour duration would have permitted convening a MRB. The FOT mission manager made the hurried decision with the advice of a Matra Marconi Space (MMS) engineer.

7. Failure to recognize risk caused by operation's team overload.

   The calibration and reconfiguration was meant to support a planned week of scientific observations and insufficient time was programmed to accomplish them, thus the hurried decisions. Such a compressed timeline had never been previously attempted and was to be accomplished without any staff augmentation. The ESR events were viewed as obstacles to accomplishing the science schedule instead of as threats to the spacecraft's health. ESR-6 occurred when the MMS engineer was troubleshooting the upcoming science maneuvers in NASA and ESA simulators.

8. Failure to recognize shortcomings in implementation of ESA/NASA agreements.

9. Emphasis on science returns was achieved at the expense of spacecraft safety.

The investigation board criticizes the decision to place management authority for the spacecraft with the SOHO Project Scientist. The investigators indicate there was a bias toward science and a lack of proper regard for spacecraft health and safety. Who should be responsible for a spacecraft is the clear issue and engineering knowledge of the craft's design and operation appears to be the crucial criteria.

10. Over-reliance of FOT on ESA and MMS representatives.

Manning levels and qualifications are a continuing theme throughout the report. The SOHO FOT had minimal training in the design and unique characteristics of the satellite for which they were responsible. They relied heavily on one each ESA and MMS engineers who were knowledgeable in the SOHO's characteristics. However, neither the FOT nor the engineer representatives knew TSTOL, the computer language used to predefine procedural sequences of ground-generated commands. Thus, nobody operating SOHO knew enough to detect the A_CONFIG_N script error!

11. Dilution of observatory engineering support.

In addition to marginal training, the FOT's workload was excessively high. They were responsible for on-line real-time control of SOHO, off-line analysis, troubleshooting Control Center problems, and support ongoing ISTP re-engineering activities. The Control Center support contractor, Allied Signal, decided to eliminate the Lead Engineer position and distribute responsibilities across the Observatory Engineers and Flight Operations Manager. The FOT had no clear management focus and little flexibility in managing their ever-increasing workload. This created an atmosphere ripe for faulty decision processes.

12. Failure to resolve critical deficiency report in a timely manner.

The lack of situation awareness of Gyro-A's shut down condition was apparently a display problem. SOHO stores the last three telemetry frames that precede a safe mode (ESR) entry and transmits them to the control center. A deficiency report written 4 years before the accident stated that "the SOHO control center was unable to display this data in a convenient (user friendly) format, was never resolved. Ironically, this feature had been included into the newly configured International Solar and Terrestrial Program (ISTP) Mission Operations Control (IMOC) Center; and although the FOT had been resident in the IMOC when the first safe mode entry was triggered (ESR-5), the frozen data were not displayed. Had it been displayed, it would have become evident that Gyro-A was not spinning,

and the sequence of events that followed should have been avoided." (page 15)

13. Failure to validate the planned sequence of events in advance.

 Inadequate testing was identified as a contributing cause to the mishap. Event scripts were used without undergoing the required quality control testing.

The investigation board has done a superb job of describing the events and root causes behind those events that led to the loss of the SOHO satellite. Clearly, nearly all the identified contributing causes are human factors related. However, the report is framed in an engineering process perspective; the only mention of human factors is the acknowledgement of Dr. Mitchell of Georgia Tech as a consultant. Dr. Mitchell apparently made significant input into the analysis, but the report fails to identify the human factors issues as such. It is interesting to note that no one from either NASA or ESA with human factors experience participated in the investigation board. This lack of participation indicates that NASA's considerable human factors capabilities are not generally engaged in ground station display and control design.

3.2.3. ESA Lessons Learned

Wimmer (1997) discusses case studies of four ESA satellite failures and their causes. A unique approach was used, referring to the problem missions anonymously thus avoiding pointing fingers at particular programs. This protection is not foolproof, as people knowledgeable in the ESA Program may readily identify the missions from their descriptions. However, it is the kind of gesture needed to focus attention on the problems and lessons learned and not on the programs.

Two of the four satellites described experienced ground controller error as part of their on-orbit anomalies. Mission 2 was a communications satellite flown in the late 1980's and early 1990's with an elliptical transfer orbit to a geostationary orbit. Multiple on-board failures were confounded by operator errors during emergency sun re-acquisition. The result was loss of attitude control and draining of the spacecraft's batteries. Three weeks later, incidental charging permitted re-establishing contact with the satellite and its eventual recovery. Mission life was shortened by increased fuel recovery and damage from the satellite's weeks outside of its design parameters.

Mission 3 was an astronomical science payload in an elliptical orbit resulting from an apogee motor failure to fire to create the intended geosynchronous orbit. The science mission was still possible given the unusual orbit, but that orbital deviation significantly increased the workload of the ground controllers. The situation was further compounded by additional failures in the gyros, star mapper, and thermal control systems. Wimmer states "The danger caused by operator and procedural errors was largely a consequence of additional operational complexities caused by the new and much more constrained orbital environment. Frequent and rapid implementations of procedural changes were required. The most serious human error occurred when a ground controller uplinked a command which omitted a velocity with its exponent missing (10^{-6}). This caused the spacecraft to depart from its normal spin rate of

−168.75 arc sec/sec, transit through 0 spin, and start spinning up in the opposite direction! Fortunately, the departure from normal spin was detected and the forces were small enough to correct the condition without damage to the spacecraft.

Although not an example of human error, Mission 4 illustrated how on-board autonomous behaviors can have a negative impact on controller workload. This mission was a microgravity scientific payload in low earth orbit requiring recovery. Developed on a "cost cutting" budget, there was insufficient testing of its on-board automation. The mission would have been in serious danger if controllers had not inhibited major fault management routines. As workaround procedures were developed as the mission progressed, the danger for controller error significantly increased. The controllers prevailed and 100% of the mission objectives were achieved, but the message is clear. Modifying procedures to cope with failures and faulty automation significantly increases the opportunity for human error.

There are several recommendations Wimmer makes concerning the life cycle of space missions. The ones most appropriate to human factors are listed below.

For project management:

- Ensure proper funding for adequate staffing of mission control teams;
- The design and trade-off processes must refer to the entire system, i.e., space and ground segments and mission objectives as well as to cost/risk or cost/mission success probabilities;
- Allocate adequate industrial resources for operations analysis, preparation of operations-related documents (user's manuals), contingency recovery analysis in a timely fashion, etc., and prevent resource diversion;
- Accept recommendations from industry for problem workaround solutions only with the concurrence of the project-specific operations team;
- Provide operations related test and failure reports to the operations team; and
- On-board software maintenance must be co-located at the Mission Control Center (MCC)--the function must be fully-operational from the launch.

For spacecraft design/development/test phases:

- Design to allow enable/disable interrogation for all critical on-board control processes;
- Ensure parametric feed back in the telemetry of any control parameter in any critical control process;
- Ensure the availability of sufficient functional flexibility for the introduction of workaround fault solutions; and
- Ensure timely delivery of adequate and factually correct user-manual documentation (this must also cover the characteristics and side effects of all introduced workaround solutions).

For mission control:

- Ensure the availability of operational expertise and proper team build-up throughout the design/development phases of a project--close collaboration between project and industry (and, if applicable, other control centers involved) is mandatory;
- Ensure adequate procedural coverage of all mission–critical activities, including contingency recoveries;
- Update and validate operational procedures rapidly--subsequent to satellite degradation events;
- Ensure the delivery of an accepted ground segment at least six months prior to launch;
- Ensure all facilities and support functions from all ground segment elements are available during acceptance tests; and
- Ensure the timely availability of an adequately realistic simulator.

These recommendations are fertile grounds for research, which could significantly improve ground control of space operations.

3.2.4. Mars Climate Orbiter Loss

The Mars Climate Orbiter (MCO) was launched on 11 December 1998 to provide weather information from Mars and to provide primary communications links for the trailing Mars Polar Lander (MPL). Part of NASA's new smaller, faster, and cheaper design philosophy; MCO was developed with several cost saving features. One feature was the use of aerobraking--a trajectory that skims the target planet's atmosphere to reduce spacecraft velocity and permit Mars's gravity to capture MCO in orbit. The Mars Orbit Insertion was performed on 23 September 1999. Sometime following Mars's occultation and during aerobraking, contact with MCO was lost and the mission was declared a failure. An accident board was hurriedly convened out of concern for the MPL, which was several weeks behind MCO and which MCO was provided communications links. The findings of this board were published before MPL's Mars encounter (NASA, 10 November 1999).

A definitive cause for MCO's loss was determined through records of its trajectory. The MCO's aerobraking was planned to occur at an altitude of 210-226 km above the Martian surface. A Trajectory Correction Maneuver (TCM-4) was planned and executed on 15 September 1999. Twenty-four hours before Mars Orbital Insertion (MOI), tracking data indicated that the spacecraft might travel as close as 110 km to the surface; minimum survival altitude was 80 km. The MOI engine start took place on 23 September 1999 and Mars occlusion occurred 49 seconds earlier than predicted. There was no further communications with the spacecraft. Further analysis of tracking data coupled with the earlier than expected loss of signal led investigators to believe that the spacecraft entered the Mars atmosphere at 57 km. This was below the minimum survivable altitude, and that the spacecraft likely burned up in the Mars atmosphere or after severe damage, skipped back into planetary space. The investigation board focused on how the trajectory error was made--the answer was startling simple.

A feature of MCO's design was the use of an asymmetrical configuration of solar panels. A single solar panel projected from one side of the spacecraft (see Figure 3.2.4-1).

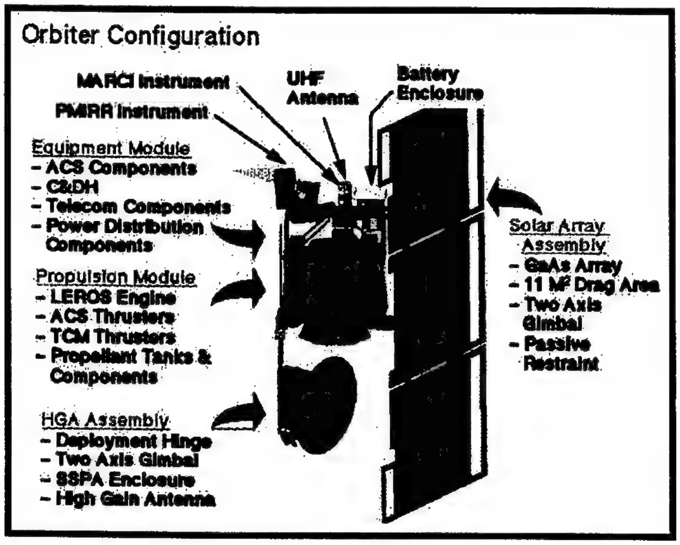


Figure 3.2.4-1.The MCO Spacecraft With Its Pronounced Asymmetrical Configuration (NASA).

This configuration causes asymmetrical forces from solar wind, causing both spacecraft rotation and deviation from the intended trajectory. A software package called "Small Forces" (SM_FORCES) is used by Jet Propulsion Laboratory (JPL) navigators to track the effects of the solar wind. Output of SM_FORCES is a file called the Angular Momentum Desaturation (AMD). Both SM_FORCES and AMD Software Interface Specification (SIS) call for forces to be input in Newton-seconds (N-s)--the appropriate metric measure for thrust. The SM_FORCES inputs were erroneously made in English units of pounds-seconds (lbf-s) instead of N-s, resulting in AMD file errors too large by a factor of 4.45--the conversion factor between lbf-s to N-s. The JPL navigators used the flawed AMD file to compute TCM-4 and that engine burn produced the fatally low encounter with the Martian atmosphere.

A series of contributing causes were identified by the MCO Accident Investigation Board and are listed below with commentary.

1. Modeling of spacecraft velocity changes.

   Software problems with the AMD file prevented its use during early parts of the MCO's planetary transit. The output of AMD was known to be anomalous, but the root cause of the errors was never identified. Direct observation by radar Doppler shift was not possible because AMD corrections occurred at right angles to the line-of-sight, rendering Doppler shift measurements impossible. Thus, the errors persisted until the MOI incident.

2. Knowledge of spacecraft characteristics.

   The investigators detected a fundamental lack of knowledge among the navigation team about the characteristics of the MCO spacecraft. A different navigation team was used during design and development, with the operations navigation team joining the project only shortly before launch. This lack of understanding about MCO and especially small force management allowed the errors in their management to persist.

3. TCM-5.

   Concern about the lower than anticipated (but still within survivable parameters) altitude for MOI produced discussion about an additional TCM-5. However, there was no detailed planning for an additional TCM and there was considerable time pressure to achieve final orbital parameters before the following MPL attempted its landing. The situation was compounded by a failure of the spacecraft operations and navigation teams to understand the potential criticality of TCM-5. TCM-5 could have prevented the loss of MCO, but was never performed.

4. Systems engineering process.

   The asymmetrical design of MCO significantly contributed to the navigation team's workload. Originally, a daily 180° flip or so-called "barbecue mode" was planned to eliminate the solar wind effects. Trade-off studies later determined that this was unnecessary and it was deleted from the mission profile. The consequence was that AMD triggered thruster firings occurred 10-14 times more frequently than anticipated in mission planning. The accumulated effects of the error in these firings over the nine month transit to Mars were what produced the trajectory error. The barbecue mode would have eliminated most of these firings and resulted in a survivable error.

5. Communication among project elements.

   Fundamental failures in communication seem to underlay the MCO loss. The navigation team assumed that MCO was similar to the earlier Mars Global Surveyor (MGS) and resulted in the navigation team failure to understand MCO operation. Whenever discrepancies in operations or navigation occurred, the teams relied on e-mail instead of the established Incident Surprise Anomaly (ISA) reporting procedure. This prevented involvement of others that might have detected the flaws in navigation and operations.

Another communications issue reported in the press, but not mentioned by the accident investigation board was that MCO's builder, Lockheed Martin, used English measurements in its design and development while NASA/JPL navigators used metric measurements. Any engineering student knows measurements such as those in thrust, especially when small in magnitude, are easily confused. Such a fundamental difference between fabricator and user seems bound to create difficulties!

6. Operations navigation team staffing.

   The Mars Surveyor Operations Project was running three missions (MGS, MCO, and MPL) simultaneously. Navigation responsibility was handled by the navigation team lead (also with responsibilities for the other two missions) and a single MCO navigator. Three full-time navigators were deemed adequate staffing, so >2 was far less than necessary. Personnel costs are a large part of overall program costs and this may be a case of where smaller, faster, and better contributed to the MCO loss.

7. Training of personnel.

   As mentioned earlier, the MCO navigation team had insufficient knowledge of the design and development of the spacecraft to adequately understand the problems they were experiencing. Some of the MCO team members were also unfamiliar with ISA reporting procedures and why it is so important. The developers of the SM_FORCES software needed additional training in following SIS guidelines. SM_FORCES Program and AMD file users were inadequately trained in the use of that software.

8. Verification and validation process.

   The software development process for SM_FORCES and the AMD file were seriously flawed. Late in development and buggy, neither was properly tested and no independent verification and validation was performed. No system verification matrix was developed and Interface Control Documents (ICDs) were not followed. One cannot help to speculate whether the SM_FORCES Program and AMD files prominently labeled the unit's input and output.

The composition of the MCO accident board is worthy of notice. The board's 19 members, advisors, and consultants do not include any human factors engineering or engineering psychology members. Recall that the SOHO investigation board at least had a human factors consultant. This exclusion of the human factors community, in investigating an accident whose causes are largely based in human error, indicates the bias engineers have toward system purely engineering views of design, development, operations, and apparently investigation of failures. There are no guarantees that greater human engineering participation in MCO's design and development would have prevented spacecraft loss. However, display design for SM_FORCES might have improved labeling of its units of measurement. Management displays of AMD ma-

neuvers exceeding expectations by 10-15 times might have raised flags about the accuracy and effects of such maneuvers. More graphical modeling and navigation displays might have permitted detection of the navigation error. Unfortunately, human factors engineering is one of the first casualties of any cost-saving campaign.

4. EXISTING RESEARCH LITERATURE

Previously, we have described press reports concerning human error in spacecraft operations and looked at several reports in detail concerning investigations of spacecraft losses. Only one of these publications was part of a published scientific paper--Wimmer (1997). A literature review was conducted to identify directly related research published concerning spacecraft control displays and controls. Apparently, there have been relatively little published in scientific journals about ground controller human factors during the 43 years of such operations.

4.1. Factors Inhibiting Open Literature on Satellite Control

Conversations with Government, Government contractors, and commercial people involved with satellite control reveal significant reasons why the satellite control literature is small. First, reports of human error represent an embarrassment which both the Government, military, and private companies would rather not publicize. There is apparently no separate satellite control human error data base with controller errors being handled at program-level unless there is a "public" loss of the satellite or its services. This unwillingness to reveal errors prevents sharing of information across programs within the Government and between Government and industry. Clearly, some form of anonymous reporting of human errors is needed like the one the FAA maintains for aircraft operations.

Second, satellite displays and controls are typically the domain of production software engineers, who burdened by delivery schedule, do not typically publish beyond internal documentation. Little or no participation by human factors specialists in the accident reports belies the fact that such specialists are not typically called upon to design ground controller displays and controls. This apparently is true even in NASA, which has a significant human factors establishment. The logic appears to be that unmanned spacecraft operations do not need human factors engineering, much less research.

4.2. Previous Scientific Literature

Brody (1993) provides a brief summary of NASA human factors research in support of the manned spaceflight program. Although he notes that space station crews will spend roughly 40% of their productive time at workstations, he only mentions ergonomic aspects of those workstation's design. There is no mention of ground controller station design efforts, a significant omission, which suggests the subject has not received much attention from the NASA human factors community.

An Air Force author (Charleton, 1992) studied satellite ground station controls in a series of quasi-experiments at Onizuka Air Force, CA. A series of questionnaires were administered to controllers who were also observed during satellite Contact Support Plan (CSP) operations. The goal was to establish an observational and questionnaire method which could be employed on a non-interference basis in operational satellite control centers.

In the first experiment, multiple regressions were calculated relating performance measures (CSP execution time, prepass execution time, contact execution time, and operator errors) with human factors measures (event counts, questionnaire ratings). Charleton found sig-

nificant multiple R^2 (.33-.79) relating both event counts (alarms encountered, warnings encountered) and questionnaire ratings (equipment design, noise levels, and fatigue).

In his second experiment, Charleton refines both his questionnaire (more specific questions) and his performance measures (breakdowns of errors and times to complete) and applied them to a larger sample of satellite contacts and operators. The reported multiple R^2 are larger (.31-.90), indicating his refinements are explaining more of the data's variance. In a third experiment, the findings are replicated at the Air Force Consolidated Space Operations Center (CSOC) Colorado Springs, CO. Multiple R^2 reported here on a different set of tasks (includes workload, specific equipment design, operator software interface) range from .06 -.79, with smaller ones being achieved with more detailed performance measures (time to return resources, time to log off).

Charleton's work with Air Force space operators demonstrates that non-invasive research can be done even in sensitive control facilities. He identifies specific problems from his observations such as configuration data base and telemetry routing test procedures. Audio noise was also identified which interfered with critical communications. These findings not only contribute to the human-computer interface literature, but the specific problem isolation can lead to significant improvements in control center operations.

Erickson, Hammer, Kahn, and Kazz (1995) did a case study of mission operations for the Mars Observer (MO) mission. This mission ended in failure when spacecraft contact was lost on 21 August 1992 with a hardware failure in the propulsion system--the most probable cause (Cunningham, 1997). Several innovative changes were made in MO's control--the first mission based on lower cost and more limited scientific objectives. Each of the innovations is described and their outcomes explained. Many of these innovations are human factors based or have human factor implications.

The first innovation was a distributed information architecture, which permitted remote science and engineering operations. The Magellan spacecraft had pioneered in this concept which permits principal investigators to conduct their science from the comfort of their normal facilities. This approach was seen as a resounding success, achieving lower operating costs, increasing productivity, and happier scientists who were not forced to relocate to the control center.

Part of the ground system development to support MO was the Science Operations and Planning Computer (SOPC). This was intended to be a standardized workstation to control instrument operations and to perform science data processing as a secondary role. A common workstation was intended to reduce or eliminate customized developments by individual investigators. The outcome was somewhat mixed. As some investigators embraced the SOPC and used it exclusively, others limited it to interfacing with their own host computers.

The MO spacecraft was the first to employ multi-mission support services--employing the Deep Space Network, Advanced Multi-Mission Operations Center, and the Multi-Mission Navigation Organization. The authors report that costs were somewhat higher than anticipated and changes during the flight to accommodate the multi-mission approach were more difficult and intrusive than anticipated. These disadvantages were still offset by significant cost

savings compared to a similar single-mission project. Unfortunately, there is no anticipation of the workload-related problems of the multi-mission navigation organization seven years later on the MCO.

The control theory community is actively pursuing and struggling with the issue of autonomous control of spacecraft using artificial intelligence (AI). Wan, Braspenning, and Vreeswijk (1995) review the issues associated with AI control of spacecraft. The ESA (Pidgeon, Seaton, Howard, and Peters, 1992) published the Standard Generic Approach to Spacecraft Autonomy and Automation (SGASAA). This document specifies high-level, ground-control command sequences or goals as specified by a Master Schedule and an on-board management system to manage accomplishment of the goals, and a check-out mode for fault correction. Wan *et al.* claimed that a SGASSA spacecraft is not autonomous because of the Master Schedule, human intervention is very likely, and the on-board fault correction cannot handle unforeseen problems.

The alternative approach involves a distributed AI multi-agent system (MAS) that can perform Distributed Problem Solving (DPS). A theoretic discourse dealing with the adaptive nature of the MAS/DPS architecture, how it fits into classical control law thinking, and the basis necessary conditions for a true autonomous system ensues. In an earlier work, Easter and Staehl (1984) asserted that autonomous spacecraft operations are neither achievable nor desirable. Wan *et al.* believed that such control can be achieved, but that such systems might perform "better if ground-control recommendation is available."

Wan *et al.* highlights the different levels of argument concerning the capabilities and the desirability of spacecraft automation. NASA's experiments with their Remote Agent on the Deep Space 1 spacecraft reflect early efforts to define the boundary conditions of autonomous operations. If we are to believe the continuing role for ground control advocated in their conclusions, what sort of displays and controls will be needed to facilitate interaction between the autonomous MAS/DPS spacecraft and its human "controllers?" Such displays must go beyond simple telemetry, but allow interaction with the AI's line of reasoning so that ground control can offer advice and/or consent in a meaningful fashion. This will add an entirely new dimension to the human-computer interface and it is one anticipated by such scientific authors as Arthur C. Clarke and Gene Roddenbury.

Shalin (1999) reports on a work in progress for NASA's Johnson Manned Spaceflight Center that is examining the complex and dynamic distributed work environment of the MCC. In the first year, she performed a thorough observational study of the MCC in general and the Flight Dynamics Officers (FDOs) specifically. This included direct observations made on the MCC floor during a Space Shuttle mission. These observations were coupled with NASA documentation, critical incident reviews, public domain information, and audio-visual recordings provided a comprehensive view of the FDO function. Several representations of this function, including Plan-Goal Graphing (PPG, Sewell, and Geddes, 1990) are part of the domain analysis that was performed. The analysis identified ten issues associated with improving MCC function through technology: distinguishing different computer models by enumeration, the proliferation of models, the integration of multiple tagged constraints resulting from several different mathematical processing tools, the selection of parameter values, processing time delays in the context

of interrupted time pressured work, and facilitating the reporting of software anomalies. These findings seem to match some of the root causes for the MCO spacecraft loss.

Shalin's research plan describes her intentions to expand her observation and analysis to several other flight controller positions (communications, payload, etc.) with which the FDO must work closely. The domain analysis will be expanded with emphasis on collaboration. Additionally, technology development to address the first two of the issues described above will be facilitated. Certainly Shalin's location at Wright State University makes her an excellent candidate for future collaboration.

4.3. Technology Trends in Satellite Operations

The newest development in satellite control is the development of Remote Agent (RA) by NASA. RA is an artificial intelligence-based software that can autonomously control spacecraft operations without ground controller intervention. RA was incorporated by NASA into the Deep Space 1 (DS1) spacecraft, which employed several experimental technologies.

The RA software is written in LISP and C++ and is composed of three parts: the planner scheduler (PS), the smart executive (EXEC), and the mode identification and recovery (MIR). PS produces flexible plans and specifies activities to accomplish mission goals. EXEC carries out PS's plans in a "smart" fashion. MIR, a.k.a. Livingston, monitors the health of the spacecraft and corrects problems as they occur. The three programs communicate with each other so that faults and their correction can generate modified plans and variations in execution.

The performance of RA on DS1 has been hailed a success although not without some faults (McHale, 1999). Livingston successfully reconfigured the spacecraft when "faults" were introduced in a sensor--when a thruster failure was induced, rebooted a "failed" subsystem, and modified power use when a camera was stuck "on." These induced faults triggered changes by PS and in EXEC. The testing has found some faults. RA successfully commanded the firing of the experimental Xenon ion engine, but failed to shut it down at the proper time. A software glitch affected RA's function, but the MIR software even went as far to suggest possible sources for the bug. Later, RA would successfully plan and execute an encounter with an asteroid, but DS1's camera was not properly aimed at the object.

Operator interaction with autonomous operations is an issue in a number of different satellite and uninhabited air vehicle (UAV) systems. Barnes, Wickens and Smith (2000) have data indicating that operators over-intervened in a missile defense simulation--degrading system performance. Excluding operator intervention altogether can have dire consequences. The Dark Star UAV was lost when the autonomous control system induced oscillations on takeoff. A stray radio transmission resulted in a Global Hawk UAV to execute its self-destruct maneuver. There are certainly common issues of operator interaction with autonomous systems between satellite and UAV control. These systems share common problems, though the decision and reaction timelines may differ between them. How ground controllers should interact with autonomous vehicle operations is an emerging research issue.

5. PROPOSED HUMAN ENGINEERING R&D PROGRAM

The preceding sections of this report have established that there exist significant human factors issues associated with ground control of spacecraft. Operator error has had and will continue to have a significant adverse impact on spacecraft operations. The responsibilities of ground controllers are undergoing significant changes with management of multi-spacecraft constellations, interaction with increasingly autonomous spacecraft, and increasing need for real-time spacecraft control. Currently, training is difficult because of the variety of spacecraft, their unique characteristics, and their different user interfaces. There is an increasing trend to provide controllers with intelligent aids to cope with increased spacecraft and mission sophistication--operator interaction with such aids is yet another human factors issue.

Given these challenges of the spacecraft controller's job and the increasing costs (fiscal and political) of mission failure, there is considerable justification for a comprehensive human factors engineering program. Keeping with the evolving model for immediate technology transfer to useful application, which now dominates DoD research programs, the proposed research agenda would be tightly coupled with the user community. Research would be performed as a necessary prerequisite to solving the problems plaguing the space operations community. Solutions would be developed by AFRL in conjunction with the Battle Labs and Space Command's internal engineering establishment in a closely coupled fashion. Usability and validation testing would occur in the field with real controllers to guarantee effectiveness of solutions. Further, the test or prototype systems would be developed in such a fashion that they can be immediately applied to operational settings or can be transitioned to contractors who can easily modify them for operational use at significantly reduced cost to the Air Force or commercial users. Such a technology development and transition strategy would provide the Air Force with immediate operational benefits from AFRL research and engineering efforts.

The following research areas are identified which can be pursued by a research/development paradigm which can immediately transition technical solutions to the DoD and commercial space community, and through the engineering and research necessary for solution development, make broad contributions to the human factors/human-computer interface literature.

5.1. Program Elements

5.1.1. Cognitive Engineering of Spacecraft Displays and Controls

This first program objective is perhaps the hardest to visualize and the hardest to accomplish. Cognitive engineering is a fashionable buzzword in human factors and generally refers to the application of the known phenomenon of cognitive science to the problems of user interface design (Rassmusen, Woods, and others). Current applications fall short of the rigor usually associated with the term "engineering," because the phenomenology of human cognition is not entirely understood and the methods used to translate the science to application are crude at best (Andriole and Adelman, 1988). Increasing complexity of systems, with spacecraft at or near the forefront, demand engineering methods be developed which can produce effective and reliable user interface designs. Currently, effective interfaces for spacecraft control take a slow and expensive iterative process often propelled by failure.

AFRL/HE is a nationally acknowledged archive for user interface engineering data, including cognitive data, through such publications as the Human Engineering Data Compendium, Handbook of Perception and Human Performance, and the Designer's Workbench. The cognitive data from these publications can serve as the basis for developing specific engineering methodologies to create effective human-computer interface design methods.

Following the case method used by Andriole and Adelman, interface design problems experienced by the SOC should act as the focal point for developing the engineering methods. Although the methods will be used to solve the SOC problems specifically, they should be general enough to apply to other space problems and other human-computer interfaces. Among the engineering methods which should be developed are:

- Measure and predict multi-modal display format effectiveness;
- Measure and predict mental transformation demands on the operators;
- Better cognitive task analysis methods;
- Tailoring displays to cognition and cognitive task analysis;
- Predicting training requirements for the system operators;
- Predicting the effect of intelligent aids on system performance; and
- Prediction of conditions where operators will fail.

Cognitively engineered designs would have easier to understand displays (more graphical where appropriate), require fewer mental transformations by the user, compliment human cognition with intelligent aiding, require less training, and produce fewer operator errors.

Even if these methods were only partially successful, they would provide interface designers with the means to significantly improve the design process, resulting in accelerate design timelines, reduce development cost, and eliminate expensive engineering change proposals (ECPs) which negatively impact cost and schedule.

The display and control work can also be applied to users of satellite information. Payload operators can benefit from the cognitive engineering effort, making interpretation of sensor information easier and faster. Other potential benefactors are the Aerospace Operations Centers (AOCs) who must track status and manage operations of multiple satellite systems often made up of multiple satellites to deliver information and services to theater commanders. Particularly, the 14th AOC at Vandenberg AFB, CA has been suggested as needing improved human engineering.

5.1.2. Modeling, Distributed Interactive Simulation, HLA-based Design, Testing, Exercise, and Training Paradigms

The operating characteristics of each spacecraft are modeled during development to validate engineering design. This same model is used to test scripting of maneuvers and to help isolate malfunctions. These models can be adapted to other uses by the HE program.

Since space operations are remote by their very nature, it would seem to matter little whether operators at their consoles were controlling real spacecraft or their models. Operator interfaces could be exercised against the spacecraft models to determine how the interface design affects spacecraft performance. This will provide the designers with a safe and low cost testbed with which to explore alternative designs quickly and cheaply.

If the adapted spacecraft model were made Distributed Interactive Simulation (DIS)/High-Level Architecture (HLA) compliant or if it was augmented with a DIS/HLA communications module, then operators could participate in virtual exercises. First, this would permit more realistic evaluation of operator-user interface performance. These exercises will provide realistic demands, pacing and operator workload for usability, validation testing, and for real-time control issues discussed later. Fault handling and its effect on system performance could be thoroughly explored.

Second, this would be of enormous value in developing doctrine and tactics for satellite employment. Commanders would experience first hand the effects of intelligence or communication capabilities from these exercises. SOC personnel can better understand the dynamics of system performance, discover new strategies for employing their limited resources, and better understand how system degradation can effect mission completion.

Third, significant operator training can be done in the DIS/HLA environment. AFRL/HE is already engaged in training improvement through the Small Business Innovative Research (SBIR) Program. ***SYTRONICS, Inc.***, is completing a Phase I SBIR that studied how Distributed Mission Training (DMT) can be used in team training for space operations. Both routine and infrequent procedures can be trained to precision using simulators. Fault isolation could be realistically trained and maintained. Unusual or exceptional circumstances can be presented in training that cannot be done in any other fashion. The 50th Space Wing is already procuring and training with a variety of simulators. Research simulations could contribute to this effort, drawing AFRL/HE and the operational training community closer together while still aggressively pursuing a research agenda. AFRL/HE had successfully exercised this joint training and research model with then Strategic Air Command (SAC) with the B-1B bomber Engineering Research Simulator (ERS). The ERS was built as an interim procedure trainer and trained aircrews and hosted several research studies (Marshak, Purvis, and Green, 1989). There is every reason to believe that AFSPC might benefit from the same kind of dual agenda shared simulation for satellite operations.

5.1.3. Real-time Control of Satellite Operations

A shift in satellite operations is occurring from primarily pre-scripted and scheduled operations to increasingly real-time or near real-time operations. The extreme dynamics of the battlefield in Desert Storm, including mobile tactical missile launch detection--the resulting retargeting of air assets, the rapid paced ground operations, and missile defense--all suggest an increased tempo of satellite operations.

Such extemporaneous operations may be difficult to pre-script and require significant operator intervention to ensure completion of mission objectives. The shift from scheduled

to unscheduled real-time interaction with spacecraft will significantly impact operator procedures. Additionally, there will be increasing opportunity for operator error, which may not only affect mission goals, but also be a risk to the spacecraft. Displays and controls may need reevaluation to determine if they can still meet the more demanding new operating environment. Real-time modeling may be necessary to determine the effects of untested event scripts. Also, likely is that the increased workload requires greater use of intelligent agent software assistance to satellite controllers.

5.1.4. Intelligent Agent Software to Aid Satellite Controllers

One current trend in HCI is the increasing use of intelligent agent (IA) software to assist operators in performing their duties. These agents can perform a variety of functions: monitor operator inputs for possible errors, suggest courses-of-action based on the situation, perform problem-solving or fault isolation, or predict the outcome of operator inputs. Use of such agent software is being touted as a way to reduce the size of crews and improve operator performance.

The human factors issues associated with use of IA software are not well understood. Among those issues include how the AI presents its input (advise or direct), how much users will trust the IA, and how much justification should be provided with its output. These same issues all apply to IA in the satellite controller workstation. Design of IA assistance should take into account the cognitive task analysis of the operator--delivering assistance only as required. Situations requiring aid include demand for technical knowledge beyond operator training, situations where speed of response is critical, and intervention where operators have commanded inappropriate or dangerous on-board actions.

5.1.5. Monitoring and Supervision of Satellite On-board Automation

Another trend detectable in spacecraft development is an increasing reliance on automation on-board the spacecraft. NASA's Deep Space 1 represents the leading edge of this technology, having automated planning, an action executive, and fault isolation. Increased autonomous operation relegates the ground controller to a supervisory and monitoring role rather than an active controller. Although there is no precedent in spaceflight, there is considerable precedent in aircraft. Cockpit automation had a similar affect on pilots and a number of disturbing accidents and incidents were caused by inappropriate interaction between aircrew and automation (Winer and Nagel, 1988).

The aircraft environment differs somewhat from the satellite controller because the pilot is within the vehicle. However, we already have evidence that on-satellite automation may not eliminate the need for operator supervision. Deep Space 1 successfully intercepted an asteroid while under the guidance of its automation. Unfortunately, the vehicle did not orient itself so that the asteroid appeared in its camera field-of-view. NASA declared the rendezvous a success, but the failure to image the asteroid smacked of failure to accomplish the imaging mission. Ground controller supervision of the intercept could have detected and corrected the sensor orientation problem and permitted imaging of the asteroid. Just as IA software is meant to monitor and facilitate human performance, operator monitoring, and supervision of on-board

automation can prevent the automation from making errors that jeopardize the spacecraft or its mission.

5.1.6. Creation and Maintenance of an Operator Error Data Base

This data base would be modeled after the Federal Aviation Administration's (FAA's) reporting system for pilots--where anonymous reports are recorded so that all errors are shared in the flying community. Reports of space operator errors would be collected, analyzed, and reported to the user community. Differing from Aerospace Corporation's anomaly data whose reports are made only when system degradations or losses occur, the operator error data base would require reporting even correctable operator errors. Greater error reporting without retribution will serve the operator community, promoting awareness of problems before they result in system degrade or loss. The error data base would serve as the basis for both initial and recurring training--benefiting all space operators. Such a data base would need to be strongly endorsed by United States Space Command (USSC) and AFSPC so that operators will be encouraged to make reports.

Initial development of a human error data base would be done to support the AFRL space research program. The data base would be a living testimonial to AFRL/HE's concern for operational effectiveness. Long term maintenance of the error data base could be done by AFRL scientists and engineers, or by AFRL's CSERIAC support contractor, or be incorporated into Aerospace Corporation's anomaly data base as a special category, or transitioned to Air Force's safety agencies.

5.1.7. Extension and Expansion of Display and Control Guidelines

Neither AIAA's style guide, or the HMIWG's proposed formats, go far enough to standardize displays and controls for satellite operations. The cognitive engineering initiative and validation of the hierarchy of abstraction and other constructs should be able to define at least high-level display formats for operators. These specifications for satellite controls could be used as a basis for a military standard (unlikely given the move to eliminate or dilute military standards) or be submitted to AIAA/ANSI as a replacement for the current guidelines. Widespread use of standards should be encouraged by requiring conformity on new DoD satellite system deliveries. The benefits to standardizing displays and controls would be in smaller operations crew sizes and lower training costs.

5.2. Common Program Support Elements

A research and engineering development program for HE satellite control needs several support elements to be successful. Planning for this common support can dramatically improve the program quality and significantly reduce the cost of execution. The proposed support elements include working relationships with the Air Force logistics and operations community, development of a modular common satellite model, and a capacity to support classified research.

5.2.1. Collaborative Partners in Space Research

Human factors engineering research into unmanned spaceflight control should be conducted in collaboration with Air Force, other Government and commercial interested and willing parties. Starting with AFRL, an obvious collaborator is the Space Vehicles Directorate (AFRL/VS). AFRL/VS mission is to discover, develop, integrate, and deliver affordable technologies for improved warfighting capabilities. The research effort must be coordinated with VS efforts to prevent overlap and create synergy.

There are two organizations at Schriever AFB, which can serve as technology transition partners for AFRL space human factors research. The first organization is the Space Battle Lab. The Space Battle Lab is in the operations chain-of-command, a part of SWC of AFSPC. Interaction with the operational chain-of-command increases the relevance of the research, provides access to the space controllers for design information and testing, and provides support for continued funding of research.

The second organization, which should participate in the space human factors program, is the CERES. CERES is in the procurement chain-of-command, organized under SMC of AFMC. It is actively involved with evaluating COTS satellite control systems and has existing laboratory-type resources at Schriever AFB. Close cooperation with CERES connects the research to the procurement system, offers a location for field research at USSC, and has resources that can facilitate the start-up of the AFRL research program.

Other Government agencies, which should be collaborated with, include NASA and the National Research Office (NRO). NASA sites can include Johnson Spacecraft Center who is sponsoring Shalin's work, Jet Propulsion Laboratory, and Goddard Spaceflight Center. NRO is responsible for classified satellite operations and might also benefit from efforts to increase satellite controller effectiveness. AFRL/HE has secure facilities that are suitable for classified research.

Additionally, an effort should be made to reach the other service laboratories, to NASA, and to the commercial satellite industry to create further collaborations. These organizations operate significant numbers of space systems and should be receptive to sharing information on problems and to take advantage of AFRL space-related research.

5.2.2. A Common Modular Satellite Model

The AFRL space research program should develop a COmmon Modular SAtellite Model (COMSAM) to support the various aspects of the satellite control research program. This model need not be developed from scratch, but might be based on existing models in the training and operations communities at AFSPC, NASA spacecraft models, or commercially available model software. Strict modularity and configuration control should prevent the proliferation of incompatibilities among model users and permit users to take advantage of improvements to the model. Certain elements of the model may be different, such as payload or propulsion systems, but these differences can be managed without adversely affecting the common features.

As described earlier, another feature of COMSAM should be DIS/HLA compatibility. A DIS/HLA communications module could be added that makes both satellite position and payload products available to other simulations. Data could be collected to determine how enhanced displays and controls improve system performance in as high a fidelity environment as is technically possible. Both the whole model and the communications module could be program products, which can be used by AFSPC, SMC, and others.

5.2.3. Shared Space Research Facility

Traditionally, AFRL researchers have built separate laboratories to conduct their own research into related phenomenon. This approach was inefficient, costly, and impractical given the current budget environment. The proposed approach follows after the AFRL/HE's Synthesized Immersion Research Environment (SIRE) facility where one laboratory with extraordinary resources is shared by a number of researchers. The Shared Space Research Facility (SSRF) could host the several researchers who will conduct their studies on its resources. Funding for maintaining the facility would come directly from the directorate, with individual research projects separately funded to make modifications necessary for individual work and to conduct their data collections. The SSRF should probably be located in Building 248 in the TEMPEST certified vaults B03 or B07 so that the facility can conduct classified research if so desired.

The SSRF would host one or more satellite models and could be used to simulate a SOC, the higher headquarters--AOC--or both, to study their interaction. Research will span individual console design to teaming and collaborative studies. With models capable of DIS/HLA participation, the vault should have high-speed network access with special consideration for security requirements should the facility go classified.

6. SUMMARY

The history of unmanned spaceflight operations clearly shows the impact on operations when human engineering is overlooked or ignored; the effects vary from disruption, to degrade, all the way to mission loss. The SSED data base indicates this has been a persistent and reoccurring human error problem in satellite operations. Recent mission losses by NASA underscore the dire consequences of ignoring operator error. Unmanned space operations need assistance from human engineering research to address display and control deficiencies.

Current generation satellite controller displays and controls, though workable, do little to facilitate operator situation awareness and prevent human error. This requires larger operations crews and labor intensive cross checks for quality control--expensive labor is being used in lieu of effective control systems. Poor display and control design combined with lack of standardization among different satellite systems places an enormous burden on the training community to maintain a proficient spacecraft controller force. Continuing budget pressure on the Air Force will quickly make trading labor for adequate display and control technology unacceptable.

A comprehensive program is proposed to address the controller interface deficiencies. The proposal includes elements with immediate benefits to the satellite control community (operator error data base, modeling and HLA simulation, and intelligent aiding) as well as fostering leading edge research to achieve longer-term benefits (cognitive engineering, real-time control, interaction with automation, and design guidelines). Additionally, recommendations are made about methods, modeling approach, and sharing resources to make the program cost-effective.

The Air Force, DoD, NASA, NRO, and commercial satellite operators can all benefit from the proposed research. Collaboration among these satellite users can reduce costs and maximize program benefits.

7. GLOSSARY OF TERMS AND ABBREVIATIONS

AFMC	Air Force Materiel Command
AFRL	Air Force Research Laboratory
AFSPC	Air Force Space Command
AI	Artificial Intelligence
AIAA	American Institute of Aeronautics and Astronautics
ANSI	American National Standards Institute
AMD	Angular Momentum Desaturation
AOC	Aerospace Operations Center
CERES	Center for Research Support
COMSAM	Common Modular Satellite Model
CSOC	Consolidated Space Operations Center
CSP	Contact Support Plan
DIS	Distributed Interactive Simulation
DMT	Distributed Mission Training
DPS	Distributed Problem Solving
DS1	Deep Space 1
ECP	Engineering Change Proposal
ERS	Engineering Research Simulator
ESR	Emergency Sun Reacquisition
ESA	European Space Agency
EXEC	Executive
FAA	Federal Aviation Administration
FOT	Flight Operations Team
FUSE	Far Ultraviolet Spectroscopic Explorer
GSFC	Goddard Space Flight Center, NASA
GUI	Graphical User Interface
HCI	Human–Computer Interface
HE	Human Effectiveness Directorate
HLA	High-Level Architecture
HMIWG	Human-Machine Interface Working Group
HST	Hubble Space Telescope
IA	Intelligent Agent
ICD	Interface Control Documents
ISA	Initial Sun Acquisition
ISC	Information Systems Center, NASA/Goddard
IMOC	ISTP Mission Operations Control Center
ISTP	International Solar and Terrestrial Program
JPL	Jet Propulsion Laboratory, NASA
MAS	Multi-Agent System
MCO	Mars Climate Observer
MGS	Mars Global Surveyor
MIR	Mode Identification and Recovery
MMS	Matra Marconi Space
MO	Mars Observer

MOI	Mars Orbital Insertion
MPL	Mars Polar Lander
NASA	National Aeronautics and Space Administration
NRO	National Reconnaissance Office
PS	Planner/Scheduler
RA	Remote Agent
SAC	Strategic Air Command
SGASAA	Standard Generic Approach to Spacecraft Autonomy and Automation
SIRE	Synthesized Immersion Research Environment
SIS	Software Interface Specification
SMC	Space and Missile Systems Center (Air Force Materiel Command)
SOC	Space Operations Center
SOPC	Science Operations and Planning Computer
SOHO	Solar Heliospheric Observatory
SSED	Space Systems Engineering Data Base
SWC	Space Warfare Center
TCM	Trajectory Correction Maneuver
UAV	Unmanned or Uninhabited Air Vehicle
USSC	United States Space Command

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